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Advancements in Digital Modulation Techniques for Enhancing Wireless Communication Systems' Performance and Security

Siddharth Jagirdar
M. Tech. in Electronics & Communication Engineering, CBS Group of Institutions, Jhajjar, Haryana.

Sannam
A.P ECE Department, CBS Group of Institutions, Jhajjar, Haryana.

ABSTRACT

Wireless communication systems have evolved significantly to meet the rising demand for high-speed data, reliable connectivity, energy efficiency, and security. This evolution is driven by advancements in digital modulation techniques, including adaptive modulation, AI-based optimization, and MIMO-OFDM systems. Traditional schemes, such as ASK and QAM, are being replaced by advanced methods that improve spectral efficiency and reduce bit error rates. Innovations like 3D-HQAM and AI-driven hybrid optimization algorithms enhance system performance in noisy, fading environments. Additionally, physical-layer security and semantic communication frameworks are redefining system security and efficiency, ensuring reliable performance in complex wireless environments.

Keywords: *Wireless Communication, Digital Modulation, Adaptive Modulation, AI Optimization, Spectral Efficiency.*

I. INTRODUCTION

Wireless communication systems have undergone rapid evolution due to the increasing demand for high data rates, reliable connectivity, energy efficiency, and secure transmission. At the core of these advancements lies the development and optimization of digital modulation techniques, which determine how information is encoded onto carrier signals for transmission over noisy and fading channels. Traditional modulation schemes such as ASK, FSK, PSK, and QAM have been widely used; however, modern communication environments characterized by multipath fading, interference, and spectrum scarcity have necessitated the adoption of more advanced and adaptive modulation approaches (Bahuguna et al., 2021). In recent years, research has increasingly focused on improving system performance using multi-antenna techniques, adaptive modulation, higher-order constellations, AI-based optimization, and physical-layer innovations. For instance, MIMO and OFDM-based systems have demonstrated significant improvements in spectral efficiency and bit error rate (BER) reduction by exploiting spatial diversity and frequency-selective channel characteristics (Muoghalu et al., 2023). Similarly, adaptive modulation schemes have been shown to dynamically adjust transmission parameters based on channel conditions such as SINR and distance, thereby improving throughput and reducing transmission errors (Khan et al., 2022). Advanced modulation research has also moved toward higher-dimensional signal representations and novel constellation designs. Kumar et al. (2025) introduced a 3D-HQAM modulation scheme, which enhances minimum Euclidean distance and improves symbol error performance in both AWGN and fading channels. These innovations reflect the continuous effort to increase spectral efficiency while maintaining acceptable error performance in increasingly complex wireless environments. Another major research direction involves integrating artificial intelligence and machine learning techniques into wireless communication systems. Akpo et al. (2024) demonstrated that hybrid optimization algorithms such as Genetic Algorithm (GA) and Artificial Bee Colony (ABC) can significantly improve BER and MSE performance in MIMO-OFDM systems. Additionally, deep learning approaches such as LSTM-based demodulation systems have shown strong potential in eliminating the need for traditional feature extraction in signal detection tasks (Daldal et al., 2020). Physical layer security has also become an important aspect of wireless system design. Pareja et al. (2025) highlighted that conventional security approaches are insufficient against side-channel attacks, and proposed power consumption-based classification techniques to identify modulation schemes with high accuracy. Similarly, chaos-based secure modulation systems such as FM-ACSK have been developed to enhance confidentiality in wireless sensor networks (Capligins et al., 2023). Furthermore, emerging paradigms such as semantic communication are redefining traditional communication models by focusing on meaning-based transmission rather than bit-level accuracy. Huang et al. (2025) introduced semantic communication frameworks that utilize new metrics like Integer Error Rate (IER), demonstrating improved bandwidth efficiency and robustness under low SNR conditions. In addition to these advancements, research on antenna design and spatial modulation techniques has led to innovative systems such as joint spatial field digital modulation (JSFDM), which combines spatial encoding with conventional modulation schemes to improve energy efficiency and hardware simplicity (Chen et al., 2026). These systems eliminate the need for complex joint synchronization and signal processing, making them suitable for next-generation wireless networks.

II. RESEARCH BACKGROUND

Chen et al. (2026) proposed a joint spatial field digital modulation (JSFDM) system as an advanced extension of spatial field digital modulation (SFDM), in which information was encoded through the spatial distribution of electromagnetic fields to achieve high energy efficiency, reduced hardware complexity, and enhanced physical layer security. It was reported that the proposed JSFDM system enabled the simultaneous transmission of SFDM signals and conventional bandpass modulation signals through two independent links, namely the SFDM link and the bandpass modulation link, which shared antenna resources and excitation signals without requiring coordinated operation. The authors indicated that, unlike conventional jointly designed systems, the proposed framework eliminated the need for joint design, joint demodulation, and time synchronization. A prototype based on the IEEE 802.11n protocol was developed using a multi-mode orbital angular momentum antenna. Through simulations and experiments, the feasibility of the system was validated, and key factors affecting bit error rate performance were identified.

Salheen et al. (2026) had presented a detailed simulation-based analysis of Bit Error Rate (BER) performance for Binary Phase Shift Keying (BPSK) and Quadrature Phase Shift Keying (QPSK) modulation schemes in the context of image transmission over wireless communication systems. The study had evaluated performance under both Single-Input Single-Output (SISO) and Single-Input Multiple-Output (SIMO) configurations, particularly 1×2 and 1×4 antenna systems, under flat Rayleigh fading channel conditions. It had aimed to determine the influence of receive diversity on transmission robustness and efficiency. The findings had shown that SIMO systems, especially higher-order diversity configurations such as 1×4, significantly improved BER performance compared to SISO systems. Both BPSK and QPSK had demonstrated enhanced resistance to channel impairments with multiple receive antennas. While BPSK had exhibited better error performance in severe fading environments, QPSK had provided higher spectral efficiency with a moderate BER trade-off, while image quality degradation under fading had also been critically examined.

Pareja et al. (June 2025) had examined physical layer security as a crucial concern in embedded wireless communication devices, particularly for military, civil, intelligence, and security-oriented applications. The authors had emphasized that secure communication at the physical layer was essential for preventing unauthorized access and mitigating exploitable vulnerabilities. They had noted that most existing security techniques primarily focused on transmitted signals while often neglecting side-channel threats arising when attackers gained physical access to the device. To address this limitation, they had proposed a novel security-oriented approach by demonstrating the feasibility of distinguishing modulation schemes through power consumption analysis (PCA). Using a Field Programmable Gate Array (FPGA), they had implemented multiple modulation schemes and recorded corresponding power consumption traces. Based on these measurements, they had developed a classification model using the gradient-boosted decision tree technique. Their findings had revealed an approximate classification accuracy of 99%, thereby underscoring the effectiveness of power analysis in identifying vulnerabilities and enhancing physical layer security in embedded wireless communication systems.

Huang et al. (2025) proposed semantic communication as an effective approach for integrating intelligence with communication systems, thereby enabling more efficient and context-aware data transmission. The study introduced a bit-conversion-based semantic communication transmission framework designed to maintain compatibility with existing wireless systems. A series of end-to-end physical layer processing modules were developed, and a semantic communication simulator was constructed for implementation and performance evaluation. To enhance transmission efficiency, the authors proposed a novel physical layer metric termed Integer Error Rate (IER), which was considered more suitable than the conventional Bit Error Rate (BER) for semantic communication assessment. Based on IER, a minimum Manhattan distance constellation mapping scheme was developed to improve transmission quality under the same BER conditions. Furthermore, a hybrid joint source–channel coding and separate source–channel coding transmission scheme was introduced, which improved semantic performance, particularly PSNR in low SNR environments, while reducing bandwidth consumption by up to 50% compared with benchmark methods.

Kumar et al. (2025) had proposed a simple and effective method for constructing higher-order three-dimensional (3D) signal constellations for next-generation digital communication systems. In their study, a novel 3D hexagonal quadrature amplitude modulation (3D-HQAM) scheme had been introduced, in which constellation points were systematically arranged in a 3D signal space to form structured lattice configurations. To reduce the increased decision complexity associated with a larger number of constellation points, a dimension reduction (DR) technique had been employed, which enabled the derivation of an analytical approximation of symbol error probability (SEP) under additive white Gaussian noise (AWGN) conditions. It had been reported that the theoretical SEP results closely matched the simulation outcomes, thereby validating the proposed approach. Furthermore, the minimum Euclidean distance (MED) had shown significant improvement over conventional 2D constellations, leading to enhanced error performance, and the system's average SEP under Rayleigh fading had also been favorably analyzed.

Akpo et al. (2024) had evaluated the performance of MIMO-OFDM systems by conducting an in-depth analysis of different modulation schemes, error correction methods, and AI-driven optimization algorithms. The study had specifically investigated the influence of hybrid Genetic Algorithm (GA) and Artificial Bee Colony (ABC) techniques on optimizing Bit Error Rate (BER) and Mean Square Error (MSE) in such systems. It had also examined the role of Forward Error Correction (FEC), particularly concatenated coding schemes, in strengthening error control performance. The findings had indicated that lower-order modulation schemes produced better BER outcomes, while the efficiency of Rayleigh and Rician fading channels varied according to the applied modulation method. Through MATLAB and Simulink-based simulations, the authors had demonstrated that the integration of AI-based optimization with advanced coding techniques significantly improved system reliability and efficiency. The study had therefore provided valuable insights for the design and optimization of wireless communication systems and had established a foundation for future real-world MIMO-OFDM applications.

Effendi et al., (2024). The performance of the phase shift keying (PSK) modulation technique over additive white Gaussian noise (AWGN) and multipath propagation channels generally becomes worse for higher-order modes. Therefore, a new modulation technique should be provided in order to have a system that is capable of transmitting data with higher efficiency while maintaining better performance at the same time. This paper presents the development of a fractal wavelet packet transform incorporated within the M-ary PSK system, namely M-ary PSK orthogonal wavelet division multiplexing (OWDM), which is proposed to obtain high performance of modulation in terms of spectrum efficiency and bandwidth resources intended for wireless communication systems. To demonstrate performance improvement over a Rayleigh frequency selective fading channel and in the presence of AWGN noise, the proposed system was evaluated and compared to the basic modulation system and M-ary PSK employing orthogonal frequency division multiplexing (OFDM). The performance results show that M-ary PSK OWDM had better performance in comparison with M-ary PSK OFDM and the conventional system. By utilizing 16 subcarriers, QPSK OWDM achieved bit error rate performance improvement from 1.5 × 10-3 to 1 × 10-4 for Eb/N0 of 20 dB with efficient bandwidth.

Muoghalu et al. (2023) had reviewed the role of multiple antennas in wireless communication systems and observed that the use of multiple-input multiple-output (MIMO) technology had enhanced data transfer speed and channel capacity by creating multiple transmission paths. The authors had noted that MIMO improved system performance through reduced bit error rate (BER) and increased signal-to-noise ratio (SNR). They had further explained that orthogonal frequency division multiplexing (OFDM) had been effective in mitigating inter-symbol interference (ISI), and that the integration of MIMO with OFDM had produced the MIMO-OFDM framework. Through an empirical review and MATLAB-based simulation, the study had evaluated BER performance under different digital modulation techniques, particularly Quadrature Amplitude Modulation (QAM). The findings had indicated that lower-order modulation schemes had achieved better BER performance than higher-order schemes. Additionally, MATLAB/Simulink modeling had demonstrated that MIMO-OFDM improved wireless system performance under both Rayleigh and Rician multipath fading channels.

Capligins et al. (2023) had presented a study on a novel frequency modulated antipodal chaos shift keying (FM-ACSK) secure digital communication system intended to enhance physical layer security in wireless sensor networks (WSNs). The authors had indicated that the proposed system was developed in a fixed-point digital format, which made it suitable for implementation on field-programmable gate arrays (FPGAs). It had been reported that the system was designed to strengthen secure data transmission while maintaining compatibility with practical hardware realization. For performance assessment, the researchers had employed a Simulink-based mathematical model under an additive white Gaussian noise (AWGN) channel environment. The study findings had been illustrated through bit error ratio (BER) curves evaluated across varying signal-to-noise ratio (SNR) levels in the communication channel. Overall, the investigation had demonstrated that the FM-ACSK approach offered a promising and efficient secure communication framework for WSN applications, particularly in terms of physical layer security enhancement and reliable digital implementation.

Shankar et al. (2023) had examined the design and analysis of high-performance DSP circuits for wireless communication systems, emphasizing their growing importance in meeting the increasing demand for faster and more efficient signal processing. The authors had reported that DSP circuits were widely utilized for tasks such as filtering, modulation, demodulation, and encoding. Their study had highlighted the major challenge of balancing power consumption, performance, and area utilization in advanced DSP circuit design. To address this, they had proposed a novel hybrid algorithmic approach combining Support Vector Machine (SVM) and Convolutional Neural Network (CNN) to enhance circuit efficiency and speed. It had been noted that such algorithms could be implemented using hardware platforms including DSPs, ASICs, and FPGAs. The study had further discussed hardware optimization through layout, routing, and placement to reduce area and power consumption. Finally, performance evaluation had been carried out to ensure that the developed circuits satisfied required design specifications effectively.

Khan et al. (2022) had observed a growing trend in wireless communication research, while also identifying persistent challenges such as packet loss, limited bandwidth, and inefficient bandwidth utilization that required further investigation. In response to these limitations, the study had employed adaptive modulation under varying parameters, including signal-to-interference-plus-noise ratio (SINR) and communication channel distance. The primary objective had been to minimize bit error rate (BER), enhance throughput, and improve efficient use of available bandwidth. The authors had also examined the effects of Additive White Gaussian Noise (AWGN), Rayleigh fading, and Rician fading channels on the performance of different modulation schemes. Their simulation results had demonstrated that the proposed adaptive technique significantly improved BER and spectral efficiency in long-range communication compared with fixed modulation schemes under co-channel interference from neighboring base stations. It had further been reported that fixed modulation performed well only under specific SINR-distance conditions, whereas AWGN channels showed superior BER performance over Rayleigh and Rician channels.

Bahuguna et al. (2021) presented a concise review of various digital modulation schemes employed in wireless communication to meet the growing demands of modern digital communication systems. The study highlighted that extensive research had already been conducted on modulation techniques under diverse channel and environmental conditions. It was reported that digital modulation had played a crucial role in enhancing information capacity, improving communication quality, enabling faster system availability, and ensuring higher data security. However, the authors also noted several practical constraints, such as limited bandwidth, power availability, and inherent noise in communication systems. The review indicated that communication system designers had prioritized bandwidth efficiency with low bit error rate (BER), whereas designers of hand-held cellular devices had focused more on power efficiency. The study examined major digital modulation techniques, including ASK, PSK, FSK, DPSK, QPSK, MSK, QAM, digital optical modulation, and multicarrier modulation, and compared their suitability to identify the most appropriate schemes for different wireless communication applications.

Singh et al. (2020) examined downlink transmission from the base station to the mobile terminal in a W-CDMA system by considering M-ary Quadrature Amplitude Modulation (QAM) and Quadrature Phase Shift Keying (QPSK) schemes. The study had analyzed the performance of QPSK and 16-QAM under different channel conditions, including Additive White Gaussian Noise (AWGN), multipath Rayleigh fading, and Rician fading. Using MATLAB 7.4 for simulation, the authors had evaluated system performance in terms of Bit Error Rate (BER) and Signal-to-Noise Ratio (SNR) while accounting for multiple users, channel noise, and interference. The objective had been to identify the most suitable modulation technique for varying channel qualities in order to ensure optimum and efficient data delivery in W-CDMA networks. Their comparative analysis had focused on BER variations across different SNR levels for the selected modulation schemes. The findings indicated that the minimum BER was achieved under AWGN channel conditions, thereby demonstrating comparatively better system performance in less severe fading environments.

Daldal et al. (2020) examined the problem of demodulating high-frequency passband digital signals transmitted over long distances, where baseband digital signals were modulated using carrier waves. The study focused on commonly used transition band modulation techniques, namely ASK, FSK, and PSK, particularly relevant in wireless, ultraviolet, and infrared communication systems. The authors reported that 8-bit digital baseband data were generated in MATLAB and subjected to noise levels ranging from 5 dB to 25 dB. They proposed a novel data-driven approach in which a single deep Long Short-Term Memory (LSTM) model was employed to demodulate ASK, FSK, and PSK signals without feature extraction or hardware demodulator circuits. The model performance was evaluated using MAPE, MSE, R^2, RMSE, and NRMSE. Their findings indicated that even under the worst noise condition (5 dB), the model achieved promising MAPE values, demonstrating that the proposed LSTM-based demodulator could be reliably applied in real-world signal demodulation tasks.

Badarneh and Almehmadi (2019) investigated millimeter-wave (mm-wave) communication as a significant enabler for the advancement of fifth-generation (5G) wireless systems. The study examined the effects of different noise types and user mobility on the performance of coherent binary digital modulation schemes over mm-wave Weibull fading channels. The authors derived exact and novel closed-form expressions for the bit error rate (BER) of coherent digital modulation under additive non-Gaussian noise conditions. They also developed new exact closed-form expressions for the symbol error rate (SER) of square M-ary quadrature amplitude modulation (M-QAM) schemes. The proposed analytical formulations incorporated the mobility of wireless receivers and remained applicable for both integer and non-integer values of fading and noise shaping parameters. Furthermore, the study demonstrated that the derived expressions provided an effective framework for performance evaluation in realistic fading environments. The analytical findings were further validated through Monte Carlo simulations, confirming the accuracy and reliability of the proposed results.

III. KEY FINDINGS FROM STUDY

Author (Year)	Methodology	Modulation / Technique	Channel Model	Key Findings
Chen et al. (2026)	Experimental + prototype (IEEE 802.11n)	JSFDM + spatial field modulation	Multi-link wireless system	Improved energy efficiency, reduced complexity, better physical layer security
Salheen et al. (2026)	Simulation	BPSK, QPSK with MIMO	Flat Rayleigh fading	SIMO improves BER; 1×4 best performance
Pareja et al. (2025)	FPGA + ML classification	Power-based modulation detection	Physical layer attack scenario	99% accuracy in modulation classification
Huang et al. (2025)	Simulation framework	Semantic communication	AWGN channel	Improved bandwidth efficiency; IER better than BER
Kumar et al. (2025)	Theoretical + simulation	3D-HQAM	AWGN + Rayleigh fading	Improved Euclidean distance; lower SEP
Akpo et al. (2024)	MATLAB/Simulink	MIMO-OFDM + AI optimization	Rayleigh & Rician fading	GA-ABC improves BER and MSE

Effendi et al. (2024)	Simulation	M-ary PSK OWDM	Rayleigh fading + AWGN	Better BER than OFDM-based PSK
Muoghalu et al. (2023)	Simulation review	MIMO-OFDM with QAM	Rayleigh & Rician	Lower-order modulation gives better BER
Capligins et al. (2023)	Simulink + FPGA model	FM-ACSK chaos modulation	AWGN	Strong physical layer security performance
Shankar et al. (2023)	Hardware design + ML	DSP with SVM-CNN	Wireless systems	Improved DSP efficiency and power optimization
Khan et al. (2022)	Simulation	Adaptive modulation	AWGN, Rayleigh, Rician	Adaptive modulation reduces BER and improves throughput
Bahuguna et al. (2021)	Review	ASK, PSK, QAM, OFDM	Various	Trade-off between power efficiency and BER
Singh et al. (2020)	MATLAB simulation	QPSK, 16-QAM	AWGN, Rayleigh, Rician	AWGN gives best BER performance
Daldal et al. (2020)	Deep learning model	LSTM-based demodulation	Noisy channels (5–25 dB)	Accurate demodulation without feature extraction
Badarneh & Almehmadi (2019)	Analytical + Monte Carlo	M-QAM, binary modulation	Weibull fading	Derived BER/SER expressions validated

IV. CONCLUSION

The performance evaluation of wireless communication systems using advanced digital modulation techniques highlights a significant evolution in modern communication design, where reliability, spectral efficiency, energy optimization, and security are jointly addressed. From the reviewed literature, it is evident that traditional modulation schemes such as PSK and QAM still form the backbone of wireless transmission; however, their performance is highly dependent on channel conditions, particularly in fading and noisy environments. As a result, enhanced schemes such as MIMO-OFDM, adaptive modulation, higher-order constellation designs, and spatial-domain modulation techniques have been widely adopted to overcome these limitations. The studies consistently demonstrate that system performance improves substantially when diversity techniques like SIMO and MIMO are implemented, as they reduce bit error rate (BER) and improve signal robustness under Rayleigh and Rician fading channels. Similarly, adaptive modulation techniques dynamically optimize transmission parameters based on channel variations, leading to improved throughput and spectral efficiency. Recent advancements such as AI-based optimization methods, deep learning-based demodulation, and intelligent signal processing have further strengthened wireless system performance by enabling real-time adaptation and reducing computational complexity. Additionally, emerging approaches like semantic communication, physical layer security techniques, and multidimensional modulation schemes indicate a shift toward more intelligent and secure communication frameworks. Overall, it can be concluded that advanced digital modulation techniques, when integrated with modern technologies such as machine learning, MIMO systems, and secure communication strategies, significantly enhance the overall performance of wireless communication systems. These innovations are essential for meeting the increasing demands of next-generation wireless networks, including 5G and future 6G systems, where ultra-reliable, high-speed, and secure communication will be critical requirements.

V. FUTURE SCOPE

- **Integration of Artificial Intelligence in Modulation Design:** Future wireless systems will increasingly use machine learning and deep learning techniques to dynamically select and optimize modulation schemes based on real-time channel conditions, improving BER performance and spectral efficiency.
- **Development of 6G-Oriented Advanced Modulation Techniques:** Next-generation 6G networks will require ultra-high data rates and extremely low latency, leading to the development of hybrid and multidimensional modulation schemes such as 3D/4D constellations and spatial-domain modulation systems.
- **Enhanced Physical Layer Security Mechanisms:** Future research will focus on improving security at the physical layer using techniques like chaos-based modulation, power analysis resistance, and secure waveform design to protect against side-channel and AI-based attacks.
- **Energy-Efficient and Green Communication Systems:** There will be a strong focus on designing low-power modulation and transmission techniques, especially for IoT and edge devices, to reduce energy consumption while maintaining high performance.
- **Semantic and Context-Aware Communication Systems:** Communication systems will evolve from bit-level transmission to meaning-based (semantic) communication, enabling intelligent data transmission that reduces bandwidth usage and improves efficiency in complex wireless environments.

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